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The Physics Potential of Ground-Based Gamma-Ray Astronomy below 50 GeV

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Abstract

Currently three ground-based Air Cherenkov detectors with energy thresholds below 50 GeV are being commissioned (CELESTE and STACEE) or under construction (MAGIC Telescope). Based on the expected performance of the MAGIC Telescope and with an emphasis on those physics questions which are unique to the energy domain below 50 GeV an overview of the scientific prospects of ground-based high energy Gamma-Ray Astronomy in terms of astrophysics, cosmology and particle physics questions is given.

1 Introduction

Technical developments have so far allowed to observe the universe from radio waves to γ-rays up to about 10 GeV and from about 300 GeV up to 100 TeV. A gap has remained between 10 GeV and 300 GeV which is going to be investigated with the MAGIC Telescope currently under construction (Martinez 1999). This instrument will be an Imaging Air Cherenkov Telescope (IACT) employing advanced technology for all of its ingredients. Other ground-based projects aiming at the energy domain below 100 GeV are the solar array projects CELESTE and STACEE.

2 The Cosmological Gamma-Ray Horizon

In spite of an energy-flux sensitivity superior to the EGRET instrument onboard CGRO (for energy spectra extrapolated to higher energies), a much smaller number of sources (e.g. 2 confirmed and 3 unconfirmed extragalactic sources) has been discovered with the IACT technique above 300 GeV implying that most of the EGRET sources have spectra turning over between 10 GeV and 300 GeV. For extragalactic sources this might either be due to external absorption on the diffuse cosmological background or due to internal absorption in the sources.

That above some critical energy defining the γ-ray horizon the visible universe in high energy photons should be limited because of pair production on the cosmological low-energy diffuse background photons was first pointed out by Gould & Schréder (1966). With increasing γ-ray energy, the threshold condition is fulfilled for an increasing number of low-energy photons from the diffuse radiation background, resulting in a decreasing γ-ray horizon. Conversely, triggering at γ-ray energies lower than current IACTs can observe one will have access to a much larger fraction of the Hubble volume and thus to a much larger source population. According to the current best estimates of the diffuse background current IACTs should only be able to observe the universe out to redshifts of $z \approx 0.1$.

With the MAGIC Telescope operating above 10 GeV a large number of AGN will be observable, and a population study of all results should then reveal a plot of the highest energy seen by the MAGIC Telescope, vs redshift. The slope of the locus of energy maxima should then be proportional to the density of intergalactic target photons. However, those maximum energies which are below the locus of points, should be due to intrinsic source absorption, and can be used to constrain γ-ray production models.

The flux of the isotropic radiation background from the far-infrared to the ultra-violet is only poorly known from direct measurements. The measurement of turn-over energies in the spectra of extragalactic sources will allow to infer the low-energy background flux in a manner completely independent of conventional methods. The background radiation flux is an important observable for models of cosmic structure formation because it constitutes a convolution of the star formation history, the dust extinction history, and the evolution of the initial mass function. In addition it has some sensitivity to the existence of massive neutrinos or stable

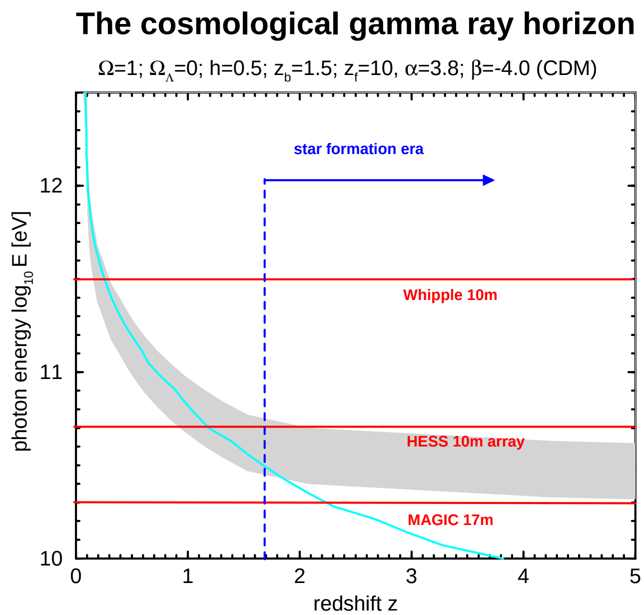

Figure 1: The shape of the γ-ray horizon resulting from a calculation by Mannheim (1999). The grey band indicates the uncertainty in the calculation due to uncertainty in the diffuse photon background level. The line is the prediction based on an extreme assumption of the star formation rate continuing at the maximum level beyond $z = 1.5$ and negligible dust absorption. For distant sources only γ-rays with energies less than the horizon can reach the observer. Taken from Mannheim (1999).

particles from supersymmetric extensions of the Standard Model acting as dark matter. In Fig. 1 the shape of the cosmological γ-ray horizon as calculated by Mannheim (1999) is shown. Also shown as horizontal lines are the lowest energies measurable by the Whipple telescope and the planned HESS array of 16 IACTs and the MAGIC Telescope in phase 1 (i.e. equipped with classical PMTs). As AGN activity seems to be linked to galaxy merger activity and the star formation era the volume density of AGN shows a prominent peak or plateau at $z \geq 1$. Only the MAGIC Telescope will thus have access to the bulk of cosmological AGN and it will be the only IACT with access to γ-rays with energies below the (possibly) asymptotic γ-ray horizon. The exact shape of the γ-ray horizon will also depend on the cosmological parameters and constitutes an important cross-check of their values determined by other means.

3 Resolving the Diffuse Gamma-Ray Background

An important scientific question closely connected to the asymptotic γ-ray horizon is the understanding of the diffuse γ-ray background in the GeV energy domain in terms of contributions from point and diffuse sources. The only known point sources today are AGN. An analysis of the AGN γ-ray luminosity function based on the EGRET results by Chiang & Mukherjee (1998) indicates that a significant fraction of the diffuse γ-ray background may be due to diffuse sources.

The emissivity of the universe at energies above the energy of the asymptotic horizon on Hubble length and Hubble time scales will appear in the diffuse γ-ray background at energies *below* the asymptotic value due to the pathlength for the cascading process (initiated at high energies due to interactions with the diffuse background) reaching a length scale of the order of the Hubble length. This also stresses the importance of the location and shape of the asymptotic γ-ray horizon. The determination of the AGN luminosity function from high sensitivity data as will be provided by the MAGIC Telescope thus is of fundamental importance for the understanding of the high energy emissivity.

Possible diffuse sources which could inject significant amounts of energy into the universe at high energies are the decays of supermassive relics from the earliest epochs, e.g. Higgs bosons in certain realizations of supersymmetric extensions of the Standard Model and topological defects.

4 Gamma-Ray Emission from Pulsars

Of the more than 800 known radio pulsars EGRET has revealed 7 to emit pulsed γ-rays up to $\approx$ 10 GeV. No steady pulsed emission from pulsars has yet been detected by ground-based IACTs above 300 GeV. To clarify the production mechanism, measurements in the 10 GeV to 100 GeV energy domain are crucial. The polar cap model for pulsed emission (Harding 1981) predicts a sharp cutoff in the γ-ray spectra above a few GeV due to absorption in the strong magnetic field. As detailed phase resolved modelling showed, the bridging emission between the two pulses should exhibit harder spectra (Daugherty & Harding 1996). This prediction was recently confirmed by phase resolved spectroscopy of the Crab, Vela and Geminga pulsars (Fierro et al. 1998) and provides a very low threshold IACT like the MAGIC Telescope with the unique opportunity to provide answers on the emission regions for the highest energy γ-rays from the neutron star magnetosphere. Phase resolved rates above 10 GeV of up to more than 100σ per hour per 0.1 phase interval (after image analysis), or more than $\sim 10\sigma$ if no background cuts are made, are estimated based on the MAGIC Telescope's sensitivity. Note that the locking onto the pulsed signal will be easily achieved and thus suppress any systematic background effects.

5 Pulsar Discovery Potential of the MAGIC Telescope

Besides the known γ-ray pulsars there is a long list of unidentified EGRET sources which seem to be coincident with massive star forming OB stellar associations (Yadigaroglu & Romani 1997). Whereas the radio signals are absorbed by the relatively high electron densities inside the OB regions, the γ-rays should escape unabsorbed. The large photon collection area of the MAGIC Telescope will allow to detect new pulsars with pulsed fluxes at 20 GeV in the order of 10^{-14} to 10^{-13} cm^{-2}s^{-1}MeV^{-1} on time scales between a few hours and a few minutes. EGRET-quiet radio pulsars should also be monitored as the flux above 100 MeV may be too small to be detectable by EGRET, but stronger than 10^{-14} cm^{-2}s^{-1}MeV^{-1} at 20 GeV. Detections of this type of pulsar would provide valuable data for the dependence of γ-ray luminosities on basic pulsar quantities (de Jager 1998).

6 Gamma-Ray Supernova Remnants

Supernova remnants (SNRs), possible sites of cosmic ray acceleration favoured in most models of the cosmic ray origin, seem to be more complex than previously believed (Jones 1997). Although four SNRs have been observed above 300 GeV (Crab nebula, Vela, PSR1706-44, and SN1006), the question of the origin of cosmic rays is far from answered. More sensitive measurements at lower energies will be of great importance in identifying the spectral component showing up above 300 GeV in the four sources above and to discover γ-ray emission in more SNRs. With the low energy threshold of the MAGIC Telescope it may be possible to observe a *two component γ-ray spectrum*, which should then allow to decouple the predicted leptonic and hadronic components in SNR shells.

7 Search for a Cold Dark Matter Candidate

Among the candidates for the dark matter in the universe, weakly interacting massive particles (WIMPs) such as the neutralinos arising in supersymmetric extensions of the standard model are the most plausible. Their interaction cross section and expected mass naturally match to produce the dominant contribution to the energy density of an expanding Friedmann-Robertson universe. With a lower limit on their mass from particle physics of about 20 GeV, the interesting mass range of ≈20 GeV to 300 GeV implies that γ-rays from decay or annihilation (neutralinos are Majorana particles) could be discovered with the MAGIC Telescope, e.g. as a γ-ray line from the region of the Galactic Centre. Note that from the northern site (La Palma) the effective photon collection area will be of the order of 10^6 m^2 which will yield sufficient sensitivity to cover a fair fraction of the MSSM parameter space (see e.g. Bergstrom et al. 1998).

8 High-Energy Counterparts of Gamma-Ray Bursts

The low moment of inertia is one of the main features of the MAGIC Telescope and it will allow rapid positioning towards observation targets (typically within 30 s). The telescope is thus ideally suited to search for high-energy counterparts of GRBs. The low-energy threshold will allow observations out to large cosmological distances. Extrapolation of the energy spectra of the GRBs detected by EGRET leads to the prediction that even medium-strength bursts will yield very high γ rates detectable by the MAGIC Telescope ($\sim$ kHz) due to the very large effective collection area. For γ rates of this magnitude the MAGIC Telescope (in phase 2) will measure energy spectra from about 5 GeV up to the highest energies.

9 Probing the Quantum Gravity Scale

Because of the high rates expected for GRBs observed with the MAGIC Telescope the high energy lightcurve of GRBs can be obtained with good temporal resolution. A number of Quantum Gravity (QG) models (Amelino-Camelia et al. 1997) predict modified laws of propagation of neutral particles as a result of interactions with the quantum gravity medium. The time delays due to the ensuing dispersion relation are only then significantly larger than the Planck time when the particles of differing energies have either energies close to the QG scale (which is expected to be close to the Planck scale, i.e.,10^{19} GeV) or have traversed cosmological distances. This last requirement is fulfilled for at least a subclass of GRB which have been observed to have redshifts up to more than 3.4. With an assumed time resolution for the lightcurve of 1 sec and a pathlength of more than several Gpc, the sensitivity of MAGIC Telescope's measurements for the QG scale will be of the order of the Planck scale. For comparison, the current best limits are about 1% of the Planck scale. Recent work within the Liouville string formulation of QG (Ellis et al. 1999) yields a refractive index which increases linearly with the photon energy, i.e. the high energy photons will arrive *later* compared to the low energy photons. This distinctive signature will help distinguishing the QG effect from classical dispersion effects which yield increasing time delays for decreasing energies.

References

Amelino-Camelia G., Ellis J., Mavromatos N. E. & Nanopoulos D. V. 1997, Mod. Phys. A12, 607
Bergstrom L., Ullio P. & Buckley J. H. 1998, Astropart. Phys. 9, 137
Chiang J. & Mukherjee R. 1998, ApJ 496, 752
Daugherty J. K. & Harding A. K. 1996, ApJ 458, 278
Ellis J., Mavromates N.E. & Nanoloulos D.V. 1999, gr-qc/9904068
de Jager O. C. 1998, Proc. 26th European Cosmic Ray Conference, Madrid, Spain, July 1998
Fierro J. M. et al. 1998, ApJ 494, 734
Gould R. J. & Schréder G., 1966, Phys. Rev. Lett. 16, 252
Harding A. K. 1981 , ApJ 245, 267
Jones T. W. 1997, astro-ph/9710227
Mannheim K. 1999, Rev. Mod. Astrophy. 12, 101
Martinez M. 1999, Proc. 26th ICRC (Salt Lake City), OG.4.3.08
Yadigaroglu I.-A. & Romani R. W. 1997, ApJ 476, 347